Global waves accompanying CMEs 140213

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14. ABSTRACT

Moreton–Ramsey waves are thin, bright wave-like features seen in Hα observations of the solar chromosphere. They are strongly associated with coronal mass ejections (CMEs) and can cover a significant portion of the Sun in under an hour. However, their origin and relationship to CMEs remains a mystery due to the manual techniques typically employed to identify and analyse them. Here we present the final report of a project developing an automated algorithm to identify, track and analyse Moreton-Ramsey waves. The Moreton Pulse Identification and Tracking Algorithm (MorePITA) uses a similar approach to the Coronal Pulse Identification and Tracking Algorithm (CorPITA), but is optimised to use Hα observations from the ISOON telescope. We describe the operation of MorePITA and its adaptation to work with other Hα instruments, potentially allowing full 24 hour coverage of the solar chromosphere. MorePITA was used to search for co-existing Moreton-Ramsey waves, "EIT waves" and CMEs although no Moreton-Ramsey waves were identified during events with observed "EIT waves". We conclude that this is due to insufficient downward pressure from the propagating "EIT wave" on the solar atmosphere. Despite successfully developing a technique to identify

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Final Report
Real–time analysis of global waves accompanying Coronal Mass Ejections

Summary

Moreton–Ramsey waves are thin, bright wave–like features seen in Hα observations of the solar chromosphere. They are strongly associated with solar eruptions and are very fast, propagating over a significant portion of the Sun in under an hour. Although initially observed in the early 1960s, what they are and how they relate to solar eruptions remains a source of mystery, mainly due to a lack of regular synoptic Hα observations and the manual techniques typically employed to identify and analyse them, which produce heavily user–biased analyses. Here we report on the final conclusions of a project to develop an automated algorithm to identify, track and analyse Moreton–Ramsey waves. The Moreton Pulse Identification and Tracking Algorithm (MorePITA) uses a similar approach to the Coronal pulse Identification and Tracking Algorithm (CorPITA), but is optimised to use Hα observations from the ISOON telescope.

We describe the operation of MorePITA and its adaptation to work with other Hα instruments, which will potentially allow full 24 hour coverage of the solar chromosphere. With MorePITA successfully developed and tested, we discuss how it was used to search for co-existing Moreton–Ramsey waves, "EIT waves" and coronal mass ejections (CMEs). However, despite the presence of multiple "EIT waves", no Moreton–Ramsey waves were identified during the same events. We conclude that this is due to an insufficient downward pressure from the propagating "EIT wave" on the solar atmosphere. Therefore, although the project successfully developed a technique for identifying Moreton–Ramsey waves, the relationship between Moreton–Ramsey waves, "EIT waves" and CMEs remains anomalous due to insufficient statistics.

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List of Symbols, Abbreviations and Acronyms

AIA Atmospheric Imaging Assembly

CME Coronal Mass Ejection

CorPITA Coronal Pulse Identification and Tracking Algorithm

EIT Extreme ultraviolet Imaging Telescope

EUV Extreme UltraViolet

EUVI Extreme UltraViolet Imager

GONG Global Oscillation Network Group

HANET Hα Network

HASTA Hα Solar Telescope for Argentina

IDL Interactive Data Language

ISOON Improved Solar Optical Observing Telescope

MorePITA Moreton Pulse Identification and Tracking Algorithm

PBD Percentage Base Difference

SDO Solar Dynamics Observatory

SOHO SOlar and Heliospheric Observatory

STEREO Solar TErrestrial RElations Observatory

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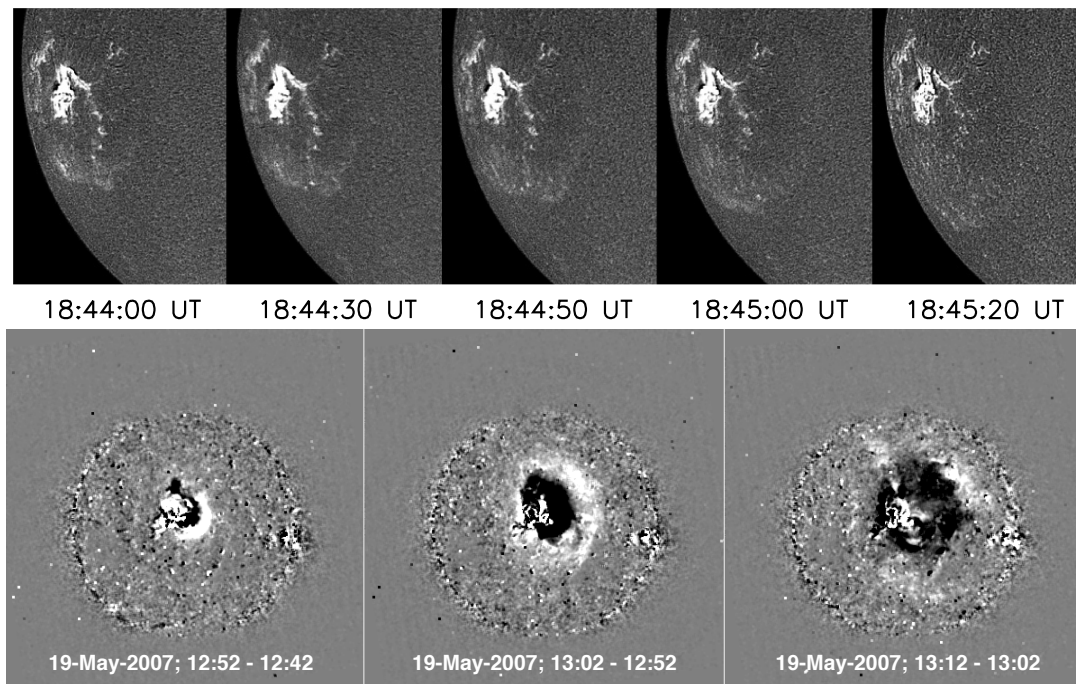
Figure 1: *Top*: A Moreton–Ramsey wave from 06 December 2006 studied by Francile et al. (2013). The thin, bright wavefront covers a significant fraction of the solar disk in under two minutes. *Bottom*: A global wave observed on 19 May 2007 by the *STEREO* spacecraft (*cf.* Long et al. 2008). The bright wave–pulse propagates across almost the entire visible solar disk in less than an hour.

1 Introduction

Global waves in the solar atmosphere were first seen in ground–based observations of the solar chromosphere using the Hα emission line. These Moreton–Ramsey waves (see Moreton 1960; Moreton & Ramsey 1960; Athay & Moreton 1961; Balasubramaniam et al. 2007, for more details) were observed as thin bright fronts propagating at speeds of ~1000–2000 km s^{-1} (see top row of Figure 1), with the result that they could traverse the solar disk in under an hour. Although following this initial observation, they were interpreted as either flows or shock waves produced by an erupting solar flare, they are strongly associated with Type II radio bursts (cf. Harvey et al. 1974) indicating the presence of a shock front. It was also noted by Uchida (1968, 1970) that the Alfvén and sound speed of the chromosphere is of the order of ~10 km s^{-1}, with the result that a wave propagating at a velocity of ~1000–2000 km s^{-1} would have a magnetosonic Mach number much greater than 1 and would disintegrate almost immediately rather than traveling the observed distances. Observations of Moreton–Ramsey waves using the wings of the Hα line also indicate a clear "down–up" swing as they propagate through the chromosphere, suggesting that something is pressing down on the chromosphere as the Moreton–Ramsey wave propagates through before the chromosphere relaxes back again (cf. Dodson & Hedeman 1964).

These observations led Uchida (1968, 1970) to suggest that the observed Moreton–Ramsey waves were not propagating in the chromosphere, but were instead the footprint of a global wave pulse moving through the solar corona above, where the sound and Alfvén speed are much higher. As this region of the solar atmosphere is best observed using extreme ultraviolet (EUV) radiation, this hypothesis remained unproven until the launch of the *Solar and Heliospheric Observatory* (*SOHO*; Domingo et al. 1995) spacecraft with its Extreme ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) in 1995.

SOHO/EIT provided the first systematic EUV observations of the low solar corona and in 1997 the first observations were made of a global wave propagating through the low solar corona (see bottom row of Figure 1 and the papers by *e.g.*, Dere et al. 1997; Moses et al. 1997; Thompson et al. 1998). This global "EIT wave" was interpreted as the coronal counterpart to the Moreton–Ramsey wave originally predicted by Uchida (1968, 1970). However, subsequent observations of significant differences between the properties and behaviour of "EIT waves" and Moreton–Ramsey waves complicated this interpretation (*e.g.*, Warmuth et al. 2004a,b). This led to an extensive debate within the community with regards to the physical properties of "EIT waves" and the nature of their relationship with Moreton–Ramsey waves.

Whereas Moreton–Ramsey waves are thin bright features propagating at speeds of ~1000–2000 km s^{-1}, the "EIT wave" pulses observed using EUV observations from *SOHO*/EIT and the subsequent *Solar Terrestrial Relations Observatory* (*STEREO*; Kaiser et al. 2008) spacecraft are much broader and more diffuse, with typical velocities of 200–400 km s^{-1} observed by Thompson & Myers (2009). Although higher average velocities closer to ~650 km s^{-1} have been observed by Nitta et al. (2013), these remain much lower than previously measured Moreton–Ramsey wave velocities.

These discrepancies between observations led to the development of a variety of alternative theories to explain the "EIT wave" phenomenon and their relationship with Moreton–Ramsey waves. Instead of being a wave pressing down on the solar chromosphere, these theories suggest that the coronal "EIT wave" is a brightening produced by the reconfiguration of the magnetic field during the eruption of a coronal mass ejection (CME; *e.g.*, Delannée et al. 2008; Attrill et al. 2007). An alternative approach suggested a hybrid interpretation, with a freely–propagating bright wavefront and a brightening corresponding to stretching of the field–lines as the CME erupts (although both features would be driven by the eruption of the associated CME, see *e.g.* Chen et al. 2002; Downs et al. 2011, for more details). However, none of these theories can fully explain all of the observed properties of both the chromospheric Moreton–Ramsey wave and the coronal "EIT wave". A more detailed description of each of these theories can be found in the recent reviews by Gallagher & Long (2011) and Warmuth (2015). How the predictions made by each theory compare to observations was also the subject of a recent International Team at the International Space Science Institute (ISSI) in Bern, Switzerland. It was found that global waves in the solar atmosphere may be best explained by a large–amplitude wave/shock interpretation, with the paper currently in review by Solar Physics (Long et al. 2016).

Although this interpretation suggests a strong correlation between Moreton–Ramsey waves and "EIT waves", the relationship between the two phenomena remains anomalous. Whereas "EIT waves" are quite frequent and have a strong relationship with CMEs, Moreton–Ramsey waves

appear to be much rarer and have no clear relationship with any other solar phenomena. However, this may be a result of the regular synoptic EUV observations available from spacecraft such as *SOHO*, *STEREO* and the *Solar Dynamics Observatory* (*SDO*; Pesnell et al. 2012) compared to the relatively low observing cadence of ground-based Hα instruments.

This discrepancy between ground–based and space–based observatories makes a detailed comparison difficult, and is particularly unfortunate as the very high observing cadence afforded by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) onboard the *SDO* spacecraft indicates that "EIT waves" may be much faster and less diffuse than originally thought (*e.g.* , Olmedo et al. 2012; Nitta et al. 2013; Long et al. 2015). This suggests that "EIT waves" and Moreton–Ramsey waves may be the result of the same phenomenon as originally suggested by Uchida (1968). However, joint observations of Moreton–Ramsey waves and "EIT waves" appear to be extremely rare, so these conclusions are primarily based on one–off studies and consequently are highly selective. Instead, both phenomena tend to be studied in isolation, leading to inconclusive results, and an over-reliance on single events as proxies for general behaviour.

The very high temporal cadence images available from *SDO*/AIA and ground-based observatories such as the Improved Solar Optical Observing Network (ISOON) have resulted in a significant increase in the amount of data available. Given the limitations of human identification of transient events, this has allowed a variety of automated algorithms to be developed to identify and analyse different phenomena. A major effort was made with the launch of *SDO* to develop automated algorithms to identify a variety of solar phenomena including active regions, solar flares, filaments and CMEs (for more details see Martens et al. 2012). This was mimicked for global coronal waves with the development of the Coronal Pulse Identification and Tracking Algorithm (CorPITA; Long et al. 2014). CorPITA was designed to automatically identify, track and analyse global coronal waves observed by *SDO*/AIA. A series of 360 10 degree wide arc sectors (each offset by 1 degree) are used to create a set of intensity profiles which are then used to identify and track the bright wavefront. This approach allows the temporal variation in position and morphology of the pulse to be tracked while minimising errors due to visual inspection.

Here we report on the conclusions of a project to extend CorPITA to work with ground-based Hα observations of the solar chromosphere. Originally designed to use data from the ISOON observatory, the Moreton Pulse Identification and Tracking Algorithm (MorePITA) has been developed to use Hα observations from any observatory, potentially allowing continuous coverage of the solar chromosphere from the ground. MorePITA was developed using a rigorous approach and includes a series of standardised testing routines that allow issues to be identified as required. As a result, MorePITA is a significant improvement on the original CorPITA code.

2   Methods, Assumptions and Procedures

While there are similarities in the behaviour and morphology of both Moreton–Ramsey waves and "EIT waves", the low solar corona and solar chromosphere are observationally very different. The solar corona is highly dynamic, with the difference between the short timescales of many coronal features (on the order of seconds to minutes) and long–lived "EIT waves"

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(which can last for up to an hour) making their identification relatively straightforward. However, Moreton–Ramsey waves evolve on a time–scale and with a length–scale comparable to that of the background solar chromosphere. This made converting CorPITA to work with Hα observations a far from trivial task and complicated the identification of Moreton–Ramsey waves. To overcome this during development of the code, difference images were produced for each event studied to allow a visual confirmation of the presence of a global wave.
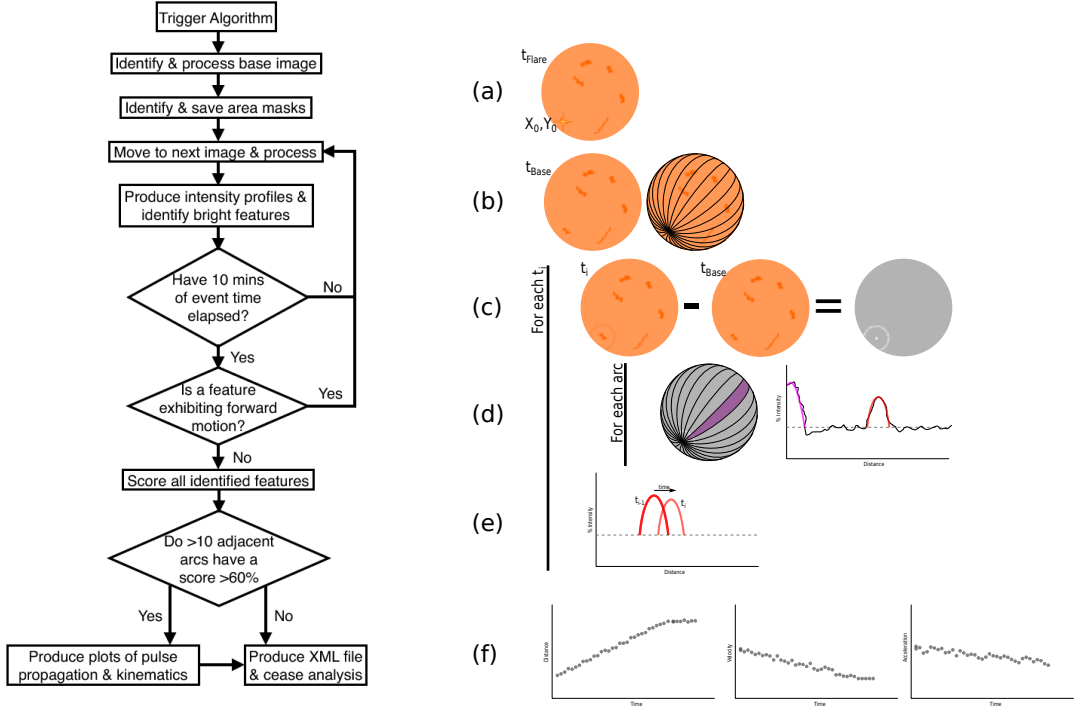
2.1 Operation of CorPITA

The CorPITA code was originally developed as a simple routine to manually identify a moving pulse in an intensity profile using *STEREO* observations (*cf.* Long et al. 2011a). However, with the launch of *SDO* it evolved to become a collection of separate codes designed to automatically identify, track and analyse global "EIT waves" using observations from *SDO*/AIA. CorPITA is designed for scientific implementation and is written using Interactive Data language (IDL), currently requiring an up-to-date *SolarSoft* distribution (*cf.* Freeland & Handy 1998) with the AIA and ONTOLOGY packages included as standard. The basic operation of the CorPITA code is described in Figure 2 and is outlined in detail in the paper by Long et al. (2014), with a brief overview provided below.

CorPITA may be run for a given solar eruption given a source point and start time, which are usually taken as the start time and location of the associated solar flare. This allows it to be triggered either manually or using a trigger algorithm such as the Flare Detective proposed by Grigis et al. (2010). The start time of the flare is used by CorPITA to identify what data to begin downloading from the Virtual Solar Observatory, while the helioprojective-cartesian coordinates of the source position allow CorPITA to measure the evolution of the pulse relative to that point. The pulse is identified using percentage base-difference (PBD) images, which subtract a pre-event "base" image from all subsequent images before dividing through by that "base" image. This is described by,

$$I_{PBD} = \frac{I_t - I_0}{I_0} \times 100, \tag{1}$$

where I_{PBD} is the percentage base difference image, I_t is the leading image and I_0 is the base image. This allows the intensity variation of the pulse to be measured as a percentage increase in intensity relative to the background corona. To mitigate against the effects of the associated solar flare, the image taken approximately two minutes prior to the start time of the flare is chosen as the "base" image.

The pulse is then identified using a series of 360 arc sectors, each of 10° width and offset by 1°, with three intensity peaks fitted in each profile. The profiles are studied iteratively, using the results from each arc sector to improve the identification of each subsequent arc sector. 10 minutes of observations are studied in the first instance to identify the presence of a pulse. If the code identifies a pulse, the process continues on an image-by-image basis until the pulse disappears. At this point, a quality control system is used to determine if a pulse was actually observed. Each of the peaks is assigned a score defined by the number of images used to identify the pulse, the fitted velocity and acceleration and the percentage uncertainty in pulse position at

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Figure 2: *Left;* A flowchart from Long et al. (2014) describing the basic operation of the CorPITA algorithm. *Right;* Schematic showing how the images are processed for each of the different steps outlined in the left–hand panel. Row a shows the base image, with row b showing the arc sectors overlaid on the leading image. Rows c to e show the creation of the difference image and identification and fitting of the peaks for each arc sector, a process repeated for each image. Finally, row f shows the distance-time plots for each identified peak.

each time–step. The quality rating score is calculated as,

$$\text{score} = \left[\left(\frac{1}{2} \times \frac{N_{\text{sector}}}{N_{\text{total}}} \right) + \frac{(v_{\text{score}} + a_{\text{score}} + \sigma^{\text{rel}}_{\text{score}})}{6} \right] \times 100, \qquad (2)$$

where N_{sector} is the number of data points corresponding to the detected pulse, N_{total} is the total number of images processed and $\sigma^{\text{rel}}_{\text{score}}$ has a value of 1 for $\sigma^{\text{rel}} < 0.5$ where σ^{rel} quantifies the uncertainty in the fitted pulse position. Similarly, v_{score} has a value of 1 for $1 < v_{fit} < 2\,000$ km s^{-1} and a_{score} has a value of 1 for $-2\,000 < a_{\text{fit}} < 2\,000$ m s^{-2} (for more details see Long et al. 2014). Finally, a summary plot is produced showing the temporal variation of the pulse overlaid on an image of the Sun along with the variation in distance of the pulse along the highest rated arc sector and the derived velocity and acceleration (see Figure 3 for details).

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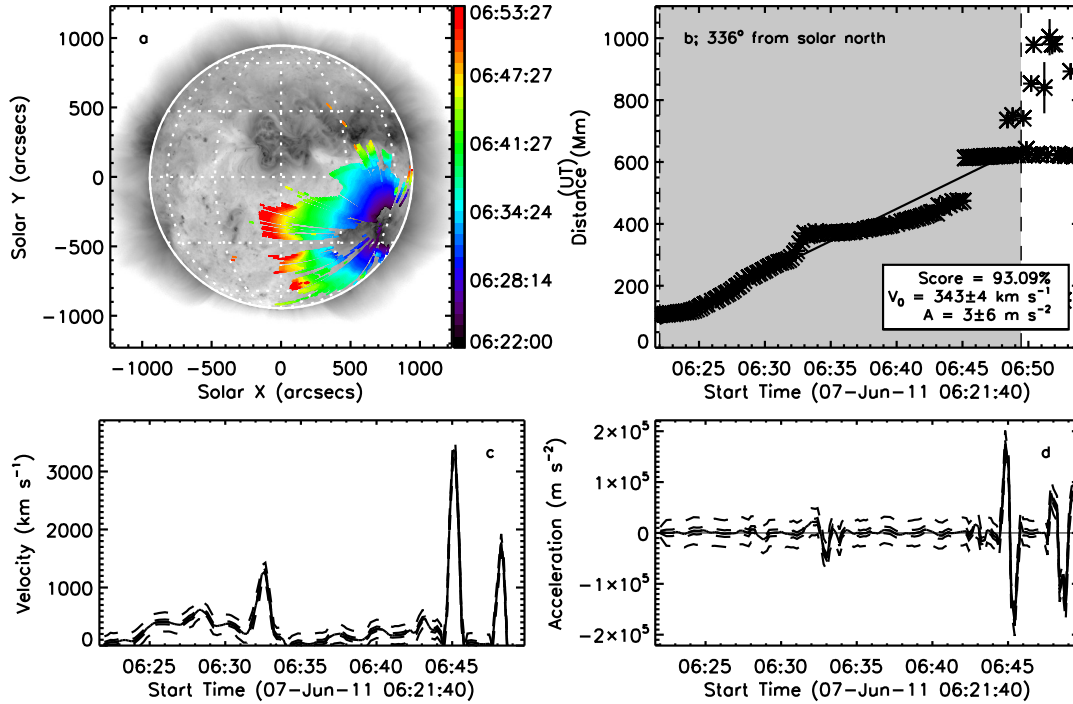
Figure 3: The output from the CorPITA code. Panel a shows the temporal variation in pulse position indicated by colour while panel b shows the fitted variation in distance with time for the highest rated arc sector (336° clockwise from solar north here). Panels c & d show the resulting variation in velocity and acceleration derived using a Savitsky–Golay interpolation, with the dashed lines indicating the associated uncertainty.

2.2 Transitioning to Hα images – MorePITA

The development of MorePITA offered an opportunity to use a comparable approach to CorPITA, but without the evolutionary and piecemeal development process. MorePITA was instead designed using a rigorous approach that included the regular deployment of testing routines to ensure the sustainable development of the code. A modular structure was also employed, allowing the code to be easily parallelised and providing the opportunity to change the detection method (for example to use a Hough transform approach similar to Kraaikamp and Verbeeck 2015) without affecting the rest of the code. MorePITA was also designed to use Hα observations from multiple telescopes to allow it to be used for continuous monitoring of the Sun from the ground. This required a detailed understanding of the complexities of both how Hα telescopes work and the region of the solar atmosphere probed using the Hα emission line.

With EUV telescopes such as *SDO*/AIA and *STEREO*/EUVI, although the resolution and cadence of the telescope may differ from instrument to instrument the basic form of the telescope remains roughly constant. Hα telescopes however have different apertures, cadence and resolu-

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tion in addition to being dependent on weather and atmospheric conditions at their site location. This complicates generalising a code such as MorePITA to work with multiple instruments such as ISOON, the Global Oscillation Network Group (GONG), the Global High Resolution Hα Network and other Hα telescopes (such as the Hα Solar Telescope for Argentina – HASTA). While generalising MorePITA to work with multiple instruments was not one of the primary aims of the project, it provides an opportunity both to benchmark performance between instruments and to have continuous coverage of the solar chromosphere. Given that one of the main reasons for the paucity of observed Moreton–Ramsey waves is the lack of complete coverage of the Sun in this passband, having a generally applicable code greatly improves our ability to identify and analyse these events.

Two Moreton–Ramsey wave events were chosen as test events to test the MorePITA code; the event from 06 December 2006 observed by ISOON and previously studied by Balasubramaniam et al. (2007) and a more recent event from 29 March 2014 observed by the HASTA observatory in Argentina that is the subject of a paper recently accepted for publication in Solar Physics by Francile et al. (2016). Examining the event from 06 December 2006 ensures that the algorithm works well with ISOON observations, while the 29 March 2014 event allows the algorithm to be tailored to a different telescope as well as providing observations of an event that was simultaneously well–observed in the EUV by *SDO*/AIA. We use these events to examine the capabilities of MorePITA in Section 3.

It should also be noted that while space–based observatories tend to use a standardised data format and pursue an open–access data policy, data from ground-based telescopes tends to follow an instrument-specific format. As a result, they do not tend to follow standard rules for recording information about the telescope, observing conditions or format of the data. This forces different observations from different telescopes to be handled in different ways. Although MorePITA was designed to use the most common software typically used to reduce ground-based Hα observations, different instruments have individual characteristics which have been identified and accounted for where possible.

3 Results and Discussion

The original proposal listed two basic work packages for the project and two additional work packages that could be completed should the project be extended. The primary work packages demanded the adaptation of the CorPITA code to work with Hα data. This code would then be used to examine the relationship between Moreton–Ramsey waves and coronal "EIT waves".

The project has been very successful. The concepts underpinning CorPITA have been successfully adapted to work with Hα observations, leading to the development of the MorePITA code. Work Package 1 can therefore be considered to be completed. The code and its application to the test data sets is discussed in more detail in Section 3.1

However, the only Moreton–Ramsey waves identified using the ISOON database (as well as the data available from HASTA) were those from 06 December 2006 and 29 March 2014 which have been previously identified and studied in the literature (*cf.* Balasubramaniam et al. 2010;

Francile et al. 2016). The application of MorePITA to the ISOON database and the outcome of Work Package 2 is discussed in more detail in Section 3.2

3.1 Work Package 1; Development & Testing of MorePITA

Using the "EIT wave" detection code CorPITA as a guide, MorePITA was designed from the bottom-up, with a series of self-contained testing routines used during development to identify any issues with the operation of the algorithm, while a test data-set was used to check its performance. In addition to the output plots from each run of the code which may be used to check how the algorithm performed, the code was designed to produce a series of difference images for each event, allowing the user to visually identify if a Moreton–Ramsey wave was present which could not be identified by the algorithm. Although primarily used during development for testing purposes, this also provides a "quicklook data" option for future use within an event catalogue.

As noted in Section 2.2, two test events were used to ensure that the code worked as required. The two Moreton–Ramsey waves observed by both ISOON (06 December 2006; Figure 4) and HASTA (29 March 2014; Figure 5) were used as test events. These events were chosen as they were previously identified Moreton-Ramsey wave events that had been studied in the literature, as well as offering the opportunity to develop MorePITA to work with multiple telescopes.

The MorePITA analysis of the event from 06 December 2006 is shown in Figure 4, with the upper panel showing the temporal variation of the position of the detected pulse with time, while the lower panel shows the variation in pulse distance with time for the highest rated arc sector (in this case at 261° clockwise from solar north. Two things are immediately apparent from Figure 4; the cadence of ISOON is much lower than that of *SDO*/AIA (see Figure 3 for comparison) and the dynamic nature of the background chromosphere and comparable scale sizes complicate the identification of the pulse. However, it is clear that MorePITA identifies the fact that the pulse in this case is quite anisotropic and primarily propagates southward away from the source region (see Figure 1 for comparison).

It should be noted that the velocity of the pulse estimated here by MorePITA is lower than that estimated by Balasubramaniam et al. (2010), with MorePITA estimating an initial velocity of ~622 km s^{-1} as opposed to the mean velocity of 850 km s^{-1} estimated by Balasubramaniam et al. (2010). However, this is most likely due to the way that MorePITA measures the position of the wave, fitting a Gaussian to the intensity peak and using the centroid of that Gaussian as the pulse position whereas Balasubramaniam et al. (2010) used the leading edge to characterise the position of the pulse. Although the leading edge is the easiest part of the pulse to identify, using it to characterise the pulse position can lead to an overestimation of the pulse kinematics as the pulse broadens with time. This produces an estimated pulse velocity that is a combination of the true pulse velocity and the expansion speed of the pulse, potentially masking any deceleration of the pulse.

The second test event chosen was the Moreton-Ramsey wave observed on 29 March 2014 by the HASTA telescope. Unfortunately, the ISOON telescope had ceased operations by this time

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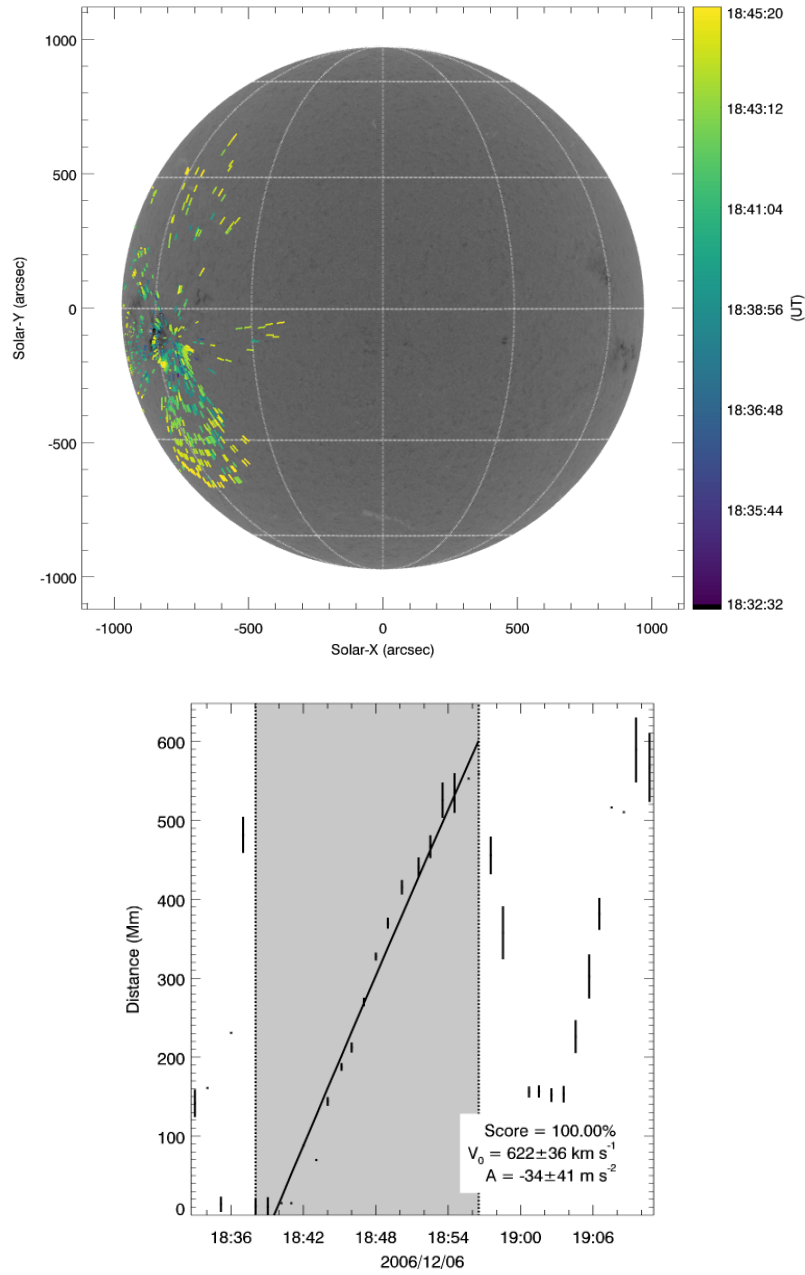
Figure 4: *Top*; Output of the MorePITA code for the 06 December 2006 Moreton–Ramsey wave event observed by ISOON. *Bottom*; Variation in pulse position with time for the highest rated arc sector at 209° clockwise from solar north. While a pulse is identified by MorePITA, as indicated by the grey region in the bottom plot, the dynamic nature of the background chromosphere makes it difficult to track with time.

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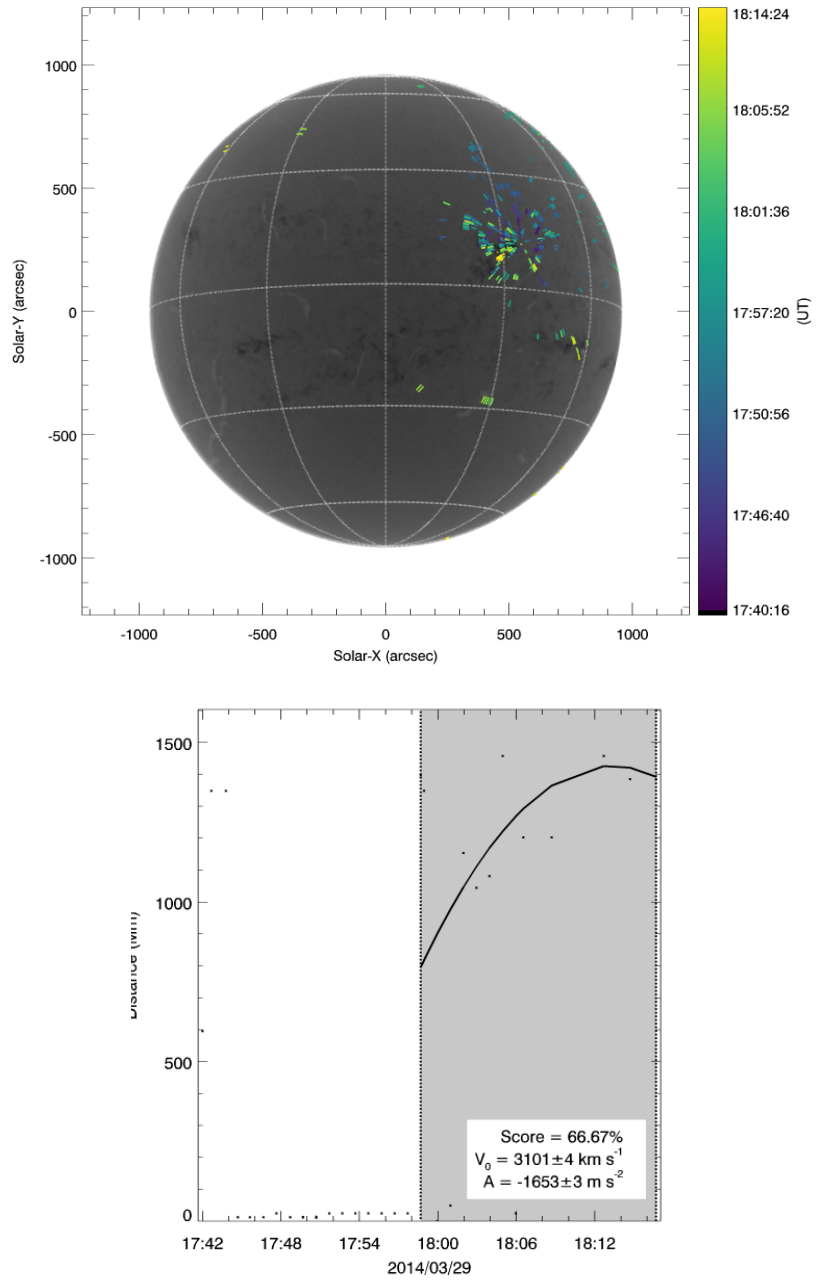
Figure 5: *Top*; Output of the MorePITA code for the 29 March 2014 Moreton–Ramsey wave event observed by HASTA. *Bottom*; Variation in pulse position with time for the highest rated arc sector at 285° clockwise from solar north. Although a pulse has again been identified, it is clear from the grey box in the bottom plot that the dynamic nature of the background chromosphere and the poorer quality of the HASTA data make this event more difficult to track with time than the 06 December 2006 event.

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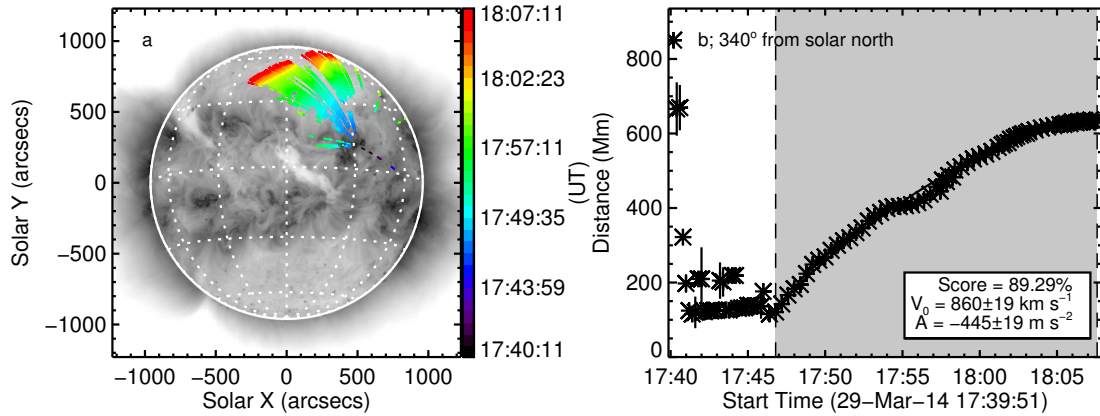
Figure 6: Output from CorPITA for the 29 March 2014 eruption in the 211 Å passband. The left panel shows the temporal variation in pulse position and the right panel shows the kinematics along the arc at 340° clockwise from solar north.

so it was not possible to analyse it using ISOON data. However, this event did offer the opportunity both to use an alternative instrument and to compare the observations with those made by *SDO*/AIA (see Figure 6). This event has been studied in detail by Francile et al. (2016), with a recently submitted paper focussed on this event in review at Solar Physics. They found that the Moreton–Ramsey wave is most likely due in this case to the "EIT wave" pressing down on the chromosphere as it propagates, in agreement with the model proposed by Uchida (1968, 1970).

It is clear from a comparison of the distance-time plots shown in Figures 5 and 6 that *SDO*/AIA has a much higher observing cadence than HASTA. The effects of turbulence in the Earth's atmosphere and the smaller aperture of the HASTA telescope are also apparent, with the very large scatter in the MorePITA detection indicating some difficulty in identifying the pulse, particularly compared to the very clear "EIT wave" detection. It should also be noted that this is a very rare event, as both Hα and EUV observations were available at relatively high temporal cadence.

As originally proposed in Work Package 1, the CorPITA code has been successfully modified to work with Hα observations and reconstituted to include more rigorous testing and error catching. The resulting MorePITA code is now available for download as a Zipped TAR file from the MSSL CorPITA website at http://www.mssl.ucl.ac.uk/missions/corpita/morepita.tar.gz. MorePITA works very well when applied to ISOON observations, using the high cadence and large aperture of the instrument to identify and analyse Moreton-Ramsey waves where possible. In addition, MorePITA has also been designed to work with Hα observations from other instruments and has been shown to successfully identify Moreton–Ramsey waves. This additional capability could potentially allow Moreton–Ramsey waves to be identified on a synoptic, 24 hour basis using telescopes from around the world. Work Package 1 has therefore been successfully completed, producing an automated algorithm that exceeds the original specification.

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3.2 Work Package 2; Relationship between Moreton–Ramsey and "EIT waves"

The aim of Work Package 2 was to take the code developed in Work Package 1 and use it to investigate the relationship between Moreton–Ramsey waves, "EIT waves" and the associated CME. To do this, a catalogue of flares was identified for which there were joint ISOON observations and *SDO*/AIA observations. Both MorePITA and CorPITA were then applied to the Hα and EUV observations to identify and analyse the Moreton–Ramsey waves and "EIT waves".

However, although a series of "EIT waves" were identified for these flares by CorPITA, no Moreton–Ramsey waves were identified by MorePITA or by visual inspection of the associated difference images. This leads to two possible conclusions; either MorePITA is not functioning as expected or the associated solar eruptions are not producing Moreton–Ramsey waves for some physical reason. Considering the rigorous testing and quality control for MorePITA outlined in Section 2.2, it must be concluded that the solar eruptions are not producing Moreton–Ramsey waves despite the presence of "EIT waves". This indicates that there is no one-to-one relationship between Moreton–Ramsey waves and "EIT waves" and that the paucity of Moreton–Ramsey waves observed since the launch of *SOHO* is due to the properties of the associated solar eruptions.

A recent paper by Vršnak et al. (2016) supports this suggestion, using a combination of simulations and modelling to conclude that a solar eruption must have sufficient energy and downward pressure on the chromosphere before it can produce a Moreton–Ramsey wave. Although the initial examination of the ISOON database using MorePITA suggests that this conclusion is correct, it requires a detailed examination of solar eruptive events both with and without Moreton–Ramsey waves for definitive proof. However, a statistical analysis of the model suggested by Vršnak et al. (2016) requires more than the two events identified to date, making confirmation of this conclusion difficult.

Although Work Package 2 proposed identifying the properties relating Moreton–Ramsey waves, "EIT waves" and CMEs, this has not been completed due to a lack of observed events. Our observations suggest that whereas "EIT waves" are relatively common, Moreton–Ramsey waves are much rarer, with the result that none were observed by ISOON during its overlap with *SDO*/AIA. Although some were observed by ISOON prior to the launch of *SDO*/AIA (such as the event from 29 October 2003 studied by Balasubramaniam et al. 2007), the very low observing cadence of *SOHO*/EIT which was observing at the time makes any comparison difficult. Work Package 2 is therefore incomplete due to a lack of observed Moreton–Ramsey wave events associated with the multiple observed "EIT waves". This is most likely a result of the insufficient downward pressure on the chromosphere exerted by these "EIT waves" as they propagated across the Sun.

3.3 Additional Work Packages

In addition to the primary Work Packages 1 and 2 originally proposed, some additional Work Packages were proposed in the event of additional funding becoming available or the project being concluded prior to the conclusion of the grant period. The aims of these Work Packages were to produce a statistical survey of CME and global waves and their collective properties and

examine the effects of different coronal and chromospheric conditions on the propagation of the global waves at both altitudes and how these affect the erupting CME. Although no additional funding was forthcoming, the lack of Moreton–Ramsey waves observed by ISOON negates the possibility of producing a statistical survey of global waves in the solar atmosphere. By extension, it is not yet possible to study their effect on the atmosphere through which they propagate.

4   Conclusions

The Moreton Pulse Identification and Tracking Algorithm (MorePITA) is a robust feature identification algorithm developed to identify, track and analyse Moreton–Ramsey waves using Hα observations of the solar chromosphere from the ISOON telescope. Although it follows a similar approach to the CorPITA code which was designed to work with EUV observations from *SDO*/AIA, it has been designed to be much more robust, with built-in testing routines and a more systematic approach. MorePITA has also been designed to be compatible with data from multiple instruments in addition to ISOON, including the HASTA and GONG telescopes. Although beyond the initial scope of the project, this allows MorePITA to potentially be used to search for Moreton–Ramsey waves on a continuous basis given the near-continuous coverage provided by different instruments around the world. The code is available as a Zipped TAR file from the MSSL CorPITA website at http://www.mssl.ucl.ac.uk/missions/corpita/morepita.tar.gz.

MorePITA was tested using a pair of well-observed Moreton–Ramsey waves; one from 06 December 2006 observed by both ISOON and HASTA and one from 29 March 2014 observed by HASTA. This provided an opportunity to ensure that the algorithm worked for different instruments of varying performance and with different properties. Although MorePITA has been shown to be able to identify the Moreton–Ramsey wave, it is clear that the aperture and therefore performance of the instrument in addition to atmospheric seeing play vital roles in the quality of the images and the intensity of the wave relative to the background chromosphere.

Upon completion of the code, it was applied to a series of solar flares observed by both ISOON and *SDO*/AIA to try and determine the relationship between Moreton–Ramsey waves, "EIT waves" and the associated CME. However, despite the presence of multiple "EIT waves" characterised by CorPITA among the events studied, no Moreton–Ramsey waves were identified. This was found to be a physical result, indicating that there is no one-to-one relationship between "EIT waves" and Moreton–Ramsey waves. This conclusion is supported by a recent paper by Vršnak et al. (2016) who found that a sufficiently energetic eruption with sufficient downward pressure is required to produce a Moreton–Ramsey wave. As a result, it was not possible to identify the properties and behaviour relating Moreton–Ramsey waves, "EIT waves" and CMEs due to a lack of observed events.

In conclusion, the project has been very successful. A new code has been developed to identify, track and analyse Moreton–Ramsey waves using synoptic Hα observations from multiple different instruments, surpassing the original specifications. Performance was found to be influenced by the instrument, with the very high signal-to-noise available from the USAF ISOON telescope allowing excellent characterisation of the Moreton–Ramsey waves. Despite the excel-

lent performance of the algorithm, no Moreton–Ramsey waves were found for events during the overlapping observing periods of ISOON and *SDO*/AIA despite the presence of multiple "EIT waves". This is most likely due to insufficient downward pressure from the associated "EIT wave" on the solar chromosphere as described by Vršnak et al. (2016).

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